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The 1996 AD delta collapse and large turbidite in Lake Brienz

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Abstract

In spring 1996 AD, the occurrence of a large mass-transport was detected by a series of events, which happened in Lake Brienz, Switzerland: turbidity increase and oxygen depletion in deep waters, release of an old corpse into surface waters and occurrence of a small tsunami-like wave. This mass-transport generated a large turbidite deposit, which is studied here by combining high-resolution seismic and sedimentary cores. This turbidite deposit correlates to a prominent onlapping unit in the seismic record. Attaining a maximum of 90 cm in thickness, it is longitudinally graded and thins out towards the end of the lake basin. Thickness distribution map shows that the turbidite extends over $\sim 8.5\ km^2$ and has a total volume of $2.72 * 10^6\ m^3$, which amounts to ~ 8.7 yr of the lake's annual sediment input. It consists of normally graded sand to silt-sized sediment containing clasts of hemipelagic sediments, topped by a thin, white, clay-sized layer. The source area, the exact dating and the possible trigger of this turbidite deposit, as well as its flow mechanism and ecological impact are presented along with environmental data (river inflow, wind and lake-level measurements). The combined results indicate that no particular cause (i.e., earthquake, explosion, flood, wind storm, lake-level change, seiche or sediment dredging) triggered the 1996 AD large turbidite deposit. Instead, it was due to a delta slope failure most likely caused by normal sediment accumulation.

Keywords: gravity flow; limnogeology; tsunami; high-resolution seismic; sediment core

1. Introduction

Mass movements and mass flows on continental slopes are of great interest for the general understanding of the sediment and rock record, and for the assessment of present and future natural hazards (Mulder and Cochonat, 1996). Lacustrine sedimentological studies on a basin-wide scale can provide detailed information that contributes to this understanding of mass movements and their related deposits. Lakes, as other confined marine environments such as, fjords and estuaries, can provide valuable data that can be potentially upscaled to model various processes in oceanic settings (Hsü and Kelts, 1985; Schnellmann et al., 2005), where basin controls and sediment sources are often more complex.

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Subaqueous gravity flows include turbidity currents and mass flows (Mulder and Alexander, 2001). They are major sediment-transporting and dispersal processes in marine and lacustrine environments, which greatly contribute to form both proximal (canyons, channel–levee, etc.) and distal (i.e., lobes) sedimentary complexes. Gravity flows are often genetically linked to mass-slides (e.g., slump, slide; Mulder and Cochonat, 1996) that eventually evolve into flows. The motion of gravity flows can induce significant disasters such as pipeline or cable breaks (amongst others, Piper et al., 1999).

Turbidite deposits are generated by turbidity currents, which originate from two different processes: the transformation of failure generated flows or the continuation of turbulent water–sediment mixture at a river mouth (hyperpycnal turbidity current). These processes exist in both lacustrine and marine realms. Gravity flow deposits, and particularly turbidite deposits, are ubiquitous in the sedimentary and rock record, and are economically important as potential hydrocarbon reservoirs.

With this study, we demonstrate that a large turbidite sediment layer was deposited in spring 1996 AD in Lake Brienz (Switzerland). Combined observations of the lake surface (small tsunami wave, release of a corpse) and deep waters (turbidity) enabled detecting this sedimentological event immediately after its triggering. From core data and seismic profiles, the lithology, thickness distribution, volume and mass of this turbidite deposit could be constrained. The combined evidence indicates that no particular triggering event (i.e., earthquake, explosion, flood, wind storm, lake-level change, seiche or sediment dredging) started this exceptionally large mass-transport.

2. Setting of Lake Brienz

Lake Brienz lies within the frontal range of the Swiss Alps (Fig. 1) in a deep longitudinal valley, which was

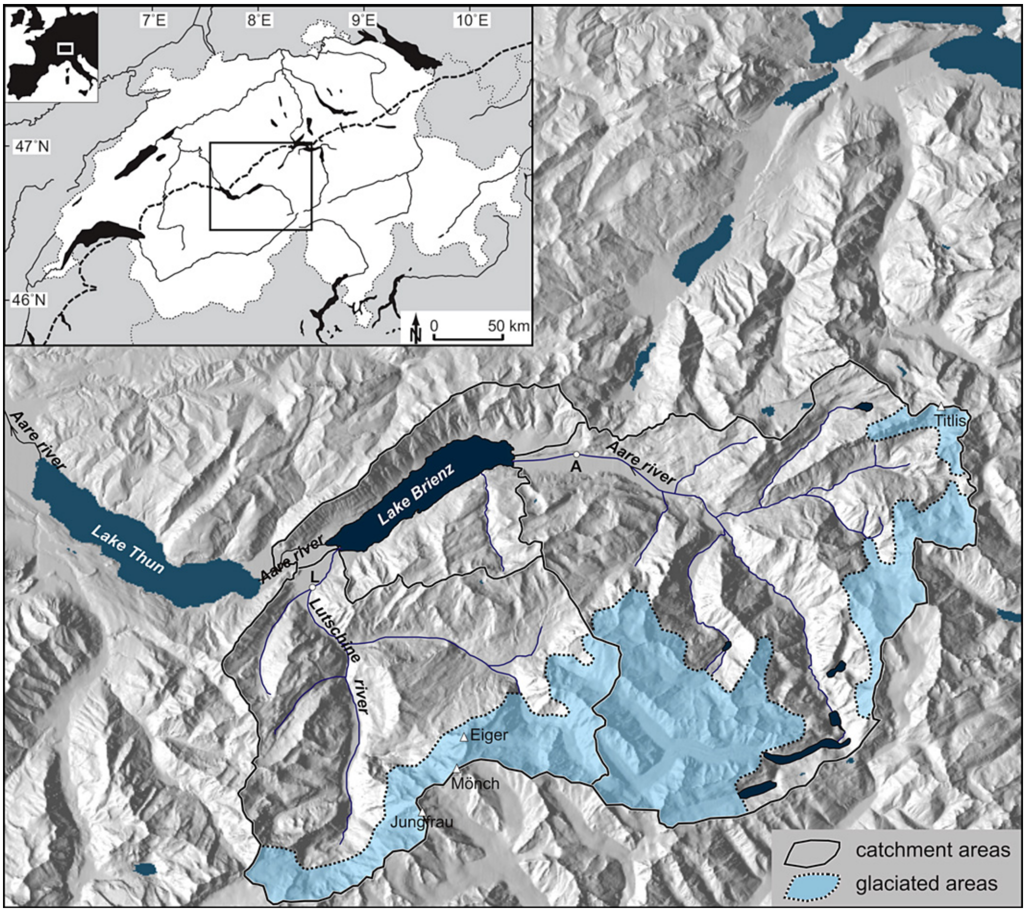

Fig. 1. Geographical map of Lake Brienz and its alpine catchment area (black line). The present glaciated area is indicated by a dotted black-white line and light blue shade (Maisch et al., 1999).

eroded by the Aare glacier during the last glaciations. This valley is situated completely within the Helvetic Nappes (Cretaceous and Jurassic calcareous formations). It is a medium-sized lake with steep flanks and a flat basin floor ~250- to 260-m-deep (Table 1 and Fig. 2). Former reflection- and refraction-seismic studies demonstrated that the lake basement forms two troughs that contain 550 and 300 m of sediment in the west and the east, respectively. The deepest, glacially-carved basement depression thus lies ~200 m below present sea-level (Matter et al., 1971).

The Lake Brienz catchment area covers 1140 km^2 and is situated in a steep, mountainous environment, partially glaciated (~19% of total area) and with 50% of its surface lying over 2000 m a.s.l. Most of the lake's catchment is drained by two large rivers, the Aare and the Lütschine (Fig. 1), which both have high water discharge in spring and early summer due to snow-melt waters. These rivers build two large deltas at either end of the lake (Adams et al., 2001). Between 1866 and 1875 AD the Aare river was canalized in the upstream alluvial plain and routed from its natural mouth to the south, where it is presently inflowing (Fig. 2). From the time it was rerouted, the Aare river has built a new delta with channels that have cut into parts of the former delta structure. The Aare and the Lütschine rivers have distinct silt- and sand-sized mineralogical signatures resulting from their geologically contrasting catchments (Sturm and Matter, 1978). A surficial sediment study showed that the sediment load of lateral streams have very little influence on total lake sedimentation compared to the two large deltas (Sturm, 1976).

Lake Brienz is holomictic and ultra-oligotrophic (Nydegger, 1967) with almost exclusively allochthonous clastic input. Sturm (1976) established that Lake Brienz sediment distribution is mainly controlled by the varying stratification of river inflows (over-, inter- and underflows). A sedimentological model for lacustrine clastic systems has been developed based on these deposits (Sturm and Matter, 1978).

Table 1
Physical characteristics of Lake Brienz (modified from Sturm and Matter, 1978)

Maximum length	14 km
Maximum width	2.5 km
Maximum depth	261 m
Surface area	30 km^2
Volume	5.2 km^3
Altitude	566 m asl
Catchment area	1140 km^2
Aare water discharge	1.195 km^3/yr (mean 1997–2004) [a]
Lütschine water discharge	0.620 km^3/yr (mean 1997–2004) [a]
Aare suspended load	128 kt/yr (mean 1997–2004) [a]
(location 'A')	176 kt/yr (maximum 1997–2004) [a]
Lütschine suspended load	174 kt/yr (mean 1997–2004) [a]
(location 'L')	242 kt/yr (maximum 1997–2004) [a]

[a] (Finger et al., 2006).

3. Methods

Seismic data were acquired during 2003 with a 3.5 kHz pinger source. A 350-m-spaced grid of seismic lines (total length 240 km) covering the entire Lake Brienz area (Fig. 2) reveals the geometry of the lake subsurface. All seismic data were digitally recorded in SEG-Y format. Data processing was carried out with SPW software and included bandpass filtering (1300-1500/6500–7000 Hz) and muting of the noise in the water column. No migration or deconvolution was applied to the data. The time-depth conversion is based on a velocity of 1450 m/s in water and 1480 m/s in sediment, as confirmed by multisensor core logging. The recording system was connected to a Differential Global Positioning System (DGPS) with a ±2–10 m positioning accuracy. For these seismic data, Rayleigh's equation (Rayleigh, 1885) gives a theoretical vertical resolution of 0.1 m for a mean seismic velocity of 1500 m/s.

The seismic dataset was interpreted in 3-D. The bathymetric map of Lake Brienz (Fig. 2) was calculated from the interpreted seismic data using radial basis interpolation in SURFER software with a resulting 50 m-spaced grid. The thickness map was calculated from core data (i.e., turbidite height) using a kriging interpolation in SURFER software. The resulting interpolated SURFER grids have 50 m spacing for x and y. The profile through interpolated grid is calculated with the SURFER 'slice' function. The bathymetry and core data grids were taken as upper and lower bounds for volume determination, which was calculated with the 'volume' function of SURFER software. This function approximates the necessary one-dimensional integrals using three classical numerical integration algorithms (Press et al., 1988).

Sediment samples were collected using a gravity corer (1–2 m length) and a modified Kullenberg coring system (5–10 m length; Kelts et al., 1986). Gamma-ray attenuation, bulk density and P-wave velocity were measured on whole-round cores using a GEOTEK multisensor core logger at the ETH Limnogeology Laboratory enabling an accurate seismic-to-core correlation. After opening, sedimentary cores were photographed, macroscopically described and sampled. Particle-size analysis of bulk sediment was performed on a Malvern Master Sizer 2000 laser diffraction instrument. Core-to-core

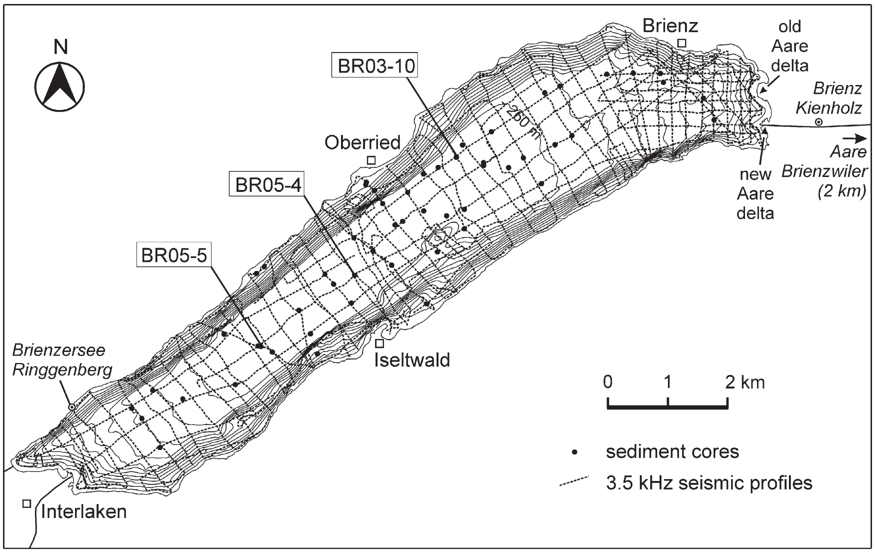

Fig. 2. Lake Brienz bathymetry map (contour lines every 20 m) showing high-resolution seismic profiles (dashed line) and sediment cores (black dots) location.

correlation was achieved by comparing both visual characteristics and lithological properties. Porosities for the different turbidite lithology classes were calculated from mean bulk density values. Dry sediment volumes were calculated from wet volumes and porosity values. Dry sediment mass was calculated from total dry volume using a given grain density of 2.65 g/cm^3.

4. Results

4.1. Observations on the 1996 event

Three intriguing circumstances, which happened in spring 1996 AD, lead to the hypothesis of the occurrence of a large mass-transport in Lake Brienz.

In May 1996, a chain of sediment-traps anchored since 1994 in central Lake Brienz could not be retrieved nor found because the acoustic release could not be triggered. During the same period, routine CTD (Conductivity–Temperature–Depth) measurements from the 'Gewässer-und Bodenschutzlabor' of Canton Bern showed extraordinary low water transparency (7-65%) and low oxygen concentration values (2–4 mg/l) in the deepest Lake Brienz waters (Fig. 3; Zeh, 1997). Normally, oxygen concentration in Lake Brienz bottom waters never falls below 6 mg/l (Liechti, 1994). Oxygen concentration isolines (mg/l) show a maximum depletion of less than 2 mg/l in June-July 1996, i.e., 1–2 mo after the occurrence of maximum turbidity. In contrast to optical transparency, which came back to normal in November 1996 (>85%, Fig. 3), oxygen concentration did not return to normal values before September 1997 (Schmidt, 1998).

On May 1st 1996, a human corpse, without head, lower legs and right arm, and partly covered by a blue vivianite coating, was found floating on the northern shore of Lake Brienz near Oberried (Fig. 1; Ammann, 1997). This so-called 'Brienzi' corpse was dated from bone-extracted collagen (180±40 ^{14}C yr BP) and from a cherry-stone sampled in its stomach (205±40 ^{14}C yr BP), which gave a weighted-mean age of 190±40 ^{14}C yr BP (cal. age lies with 58.8% within 1719–1818 AD). The official forensic investigations established that the man died by drowning, about 190–290 yr ago (Thali et al., 1998). They also concluded that, buried in the lake sediments, the corpse had been protected from oxygen-related decomposition, and that it was probably released into water by a large mass-transport event (Zeh, 1997).

On April 24th 1996, a sunny and windless day, workers from 'Aarekies AG' company were on a floating bagger anchored 130–140 m offshore 'Alter Aaregg' (old Aare delta; Fig. 1) performing dredging at 8–10 m water depth. The ~50 t dredging bagger was tightly anchored with 5 wire cables, 2 of them attached onshore and 3 anchored offshore. At about 8:00 GMT, the cable winches went surprisingly a bit backwards despite their brakes, and a loud noise raised the team's attention. Immediately after, two wire cables, one onshore and one offshore (16 mm and 19 mm diameter, respectively), broke at once. After this incident, upon reaching the harbor, the team reported that the boat was staying lower on the quay than normal. Some time later,

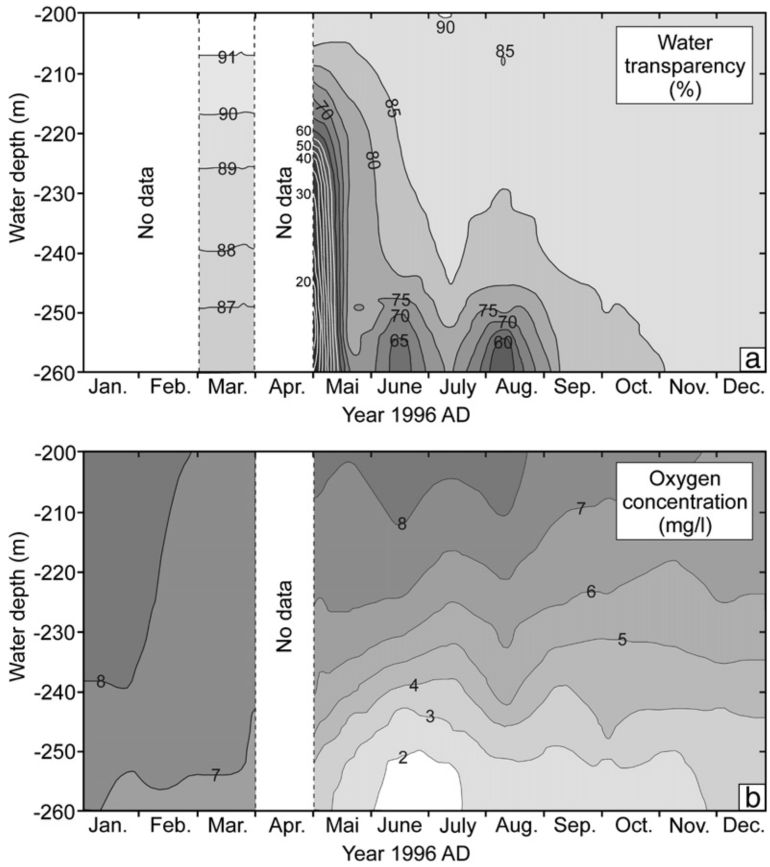

Fig. 3. Evolution of Lake Brienz deepest waters (−200 to −260 m depth) during 1996 AD from monthly CTD measurements (from Zeh, 1997): (a) water transparency isolines (%) show the drastic drop of transparency that took place after April 30th 1996. Normal water transparency values (85–100%) were reached only 6 mo later (November 1996); (b) Oxygen concentration isolines (mg/l) showing a drop of oxygen content after April 30th 1996, and a maximum depletion 1–2 mo later (June–July 1996).

the workers noted that the boat was then staying half a metre higher than its former position and deduced that the lake level was greatly fluctuating without generating any noticeable surface waves. The time period between the highest and lowest lake level (with approximately half metre amplitude) was 15–20 min (pers. comm. Jürg Gruber and Mr. Moser) and is identified as a small tsunami wave.

The combined observation data enabled a detailed tracking of the event immediately after its triggering, even before all sediment particles were settled.

4.2. Sediment cores

Four long and fifty-three short gravity cores were recovered in Lake Brienz between 1998 and 2005 (Fig. 2). Sediment from the deep lake basin is mostly silt-sized (mean particle size 2 to 20 μm) and characterized by laminations (1 mm to 1 cm thick) of varying hues (Fig. 4). These silty laminations are caused by fluctuating sediment input from Lütschine and Aare rivers, which are slowly settling down as hemipelagic deposits. Sandy deposits (1 mm to 5 cm thick) that interbed with the fine-grained hemipelagic deposits are turbidites due to river underflow events (Sturm and Matter, 1978). In the sedimentary cores recovered for this study, the 'background' sedimentation consisting of these hemipelagic deposits and small turbidites is interrupted by a distinct uniform grey 10 to 90 cm-thick sedimentary bed, which has a normally graded sand to silt grain size distribution and is topped by a thin white clay-sized layer. The graded silty unit has a mean grain size of 12 μm and a mean 1.41 g/cm^3 wet density and the graded sand unit varies from 70 to 300 μm and has a mean 1.78 g/cm^3 wet density. The top clay-sized layer has a mean grain size of 3 μm. The graded bed shows a cruder grading at its base, with a mean particle size of 100 to 300 μm (Fig. 4). Due to its lithology, this bed is interpreted as a large turbidite deposit. The upper well graded silty-topped-by-clay interval corresponds to the

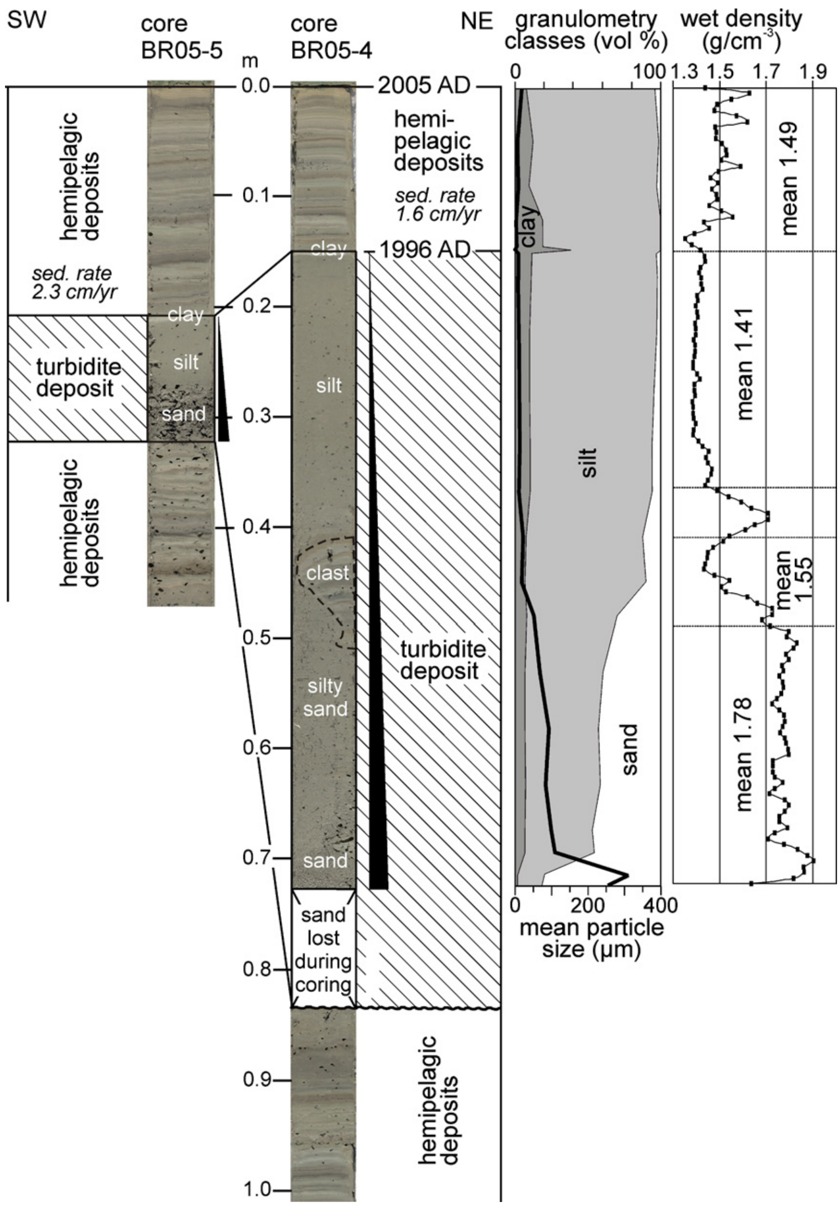

Fig. 4. Sediment cores image and lithology with hemipelagic sediment (silty laminations) and 1996 AD large turbidite deposit (grey graded bed). The turbidite deposit is graded from sand to silt and is topped by a thin white clay layer, and partly includes sediment clast of hemipelagic sediment (core BR05-4). Sedimentation rates for hemipelagic deposits vary between 1.6–2.3 cm/yr in the deep lake basin. Refer to Fig. 2 for core locations.

'E2' (Piper, 1978) or 'T6' (Stow and Shanmugam, 1980) turbidite mud facies. It directly lies on the graded sand with a crude bed base, which corresponds to the concentrated flow at base depositing the 'Ta' facies of Bouma (1962) or the concentrated flow deposit of Mulder and Alexander (2001). The embedded sediment clasts of the 1996 AD turbidite might partly correspond to the 'patchy fine silt lenses' of the 'T6' facies (Stow and Shanmugan, 1980). Using the sedimentary cores retrieved in 2005 AD, mean sedimentation rates of 2.3 cm/yr for BR05-5 and 1.6 cm/yr for BR05-4 (Fig. 4) were calculated for the hemipelagic sediments deposited after the 1996 AD turbidite event. The BR05-5 sediment core shows a higher sedimentation rate than BR05-4 because it is located closer to the Lütschine river delta (Anselmetti et al., in press).

Although the large turbidite was detected in 33 sedimentary cores, a longitudinal lake transect is reconstructed with 16 of them (Fig. 5a and b). This sediment profile reveals the varying structures of the turbidite

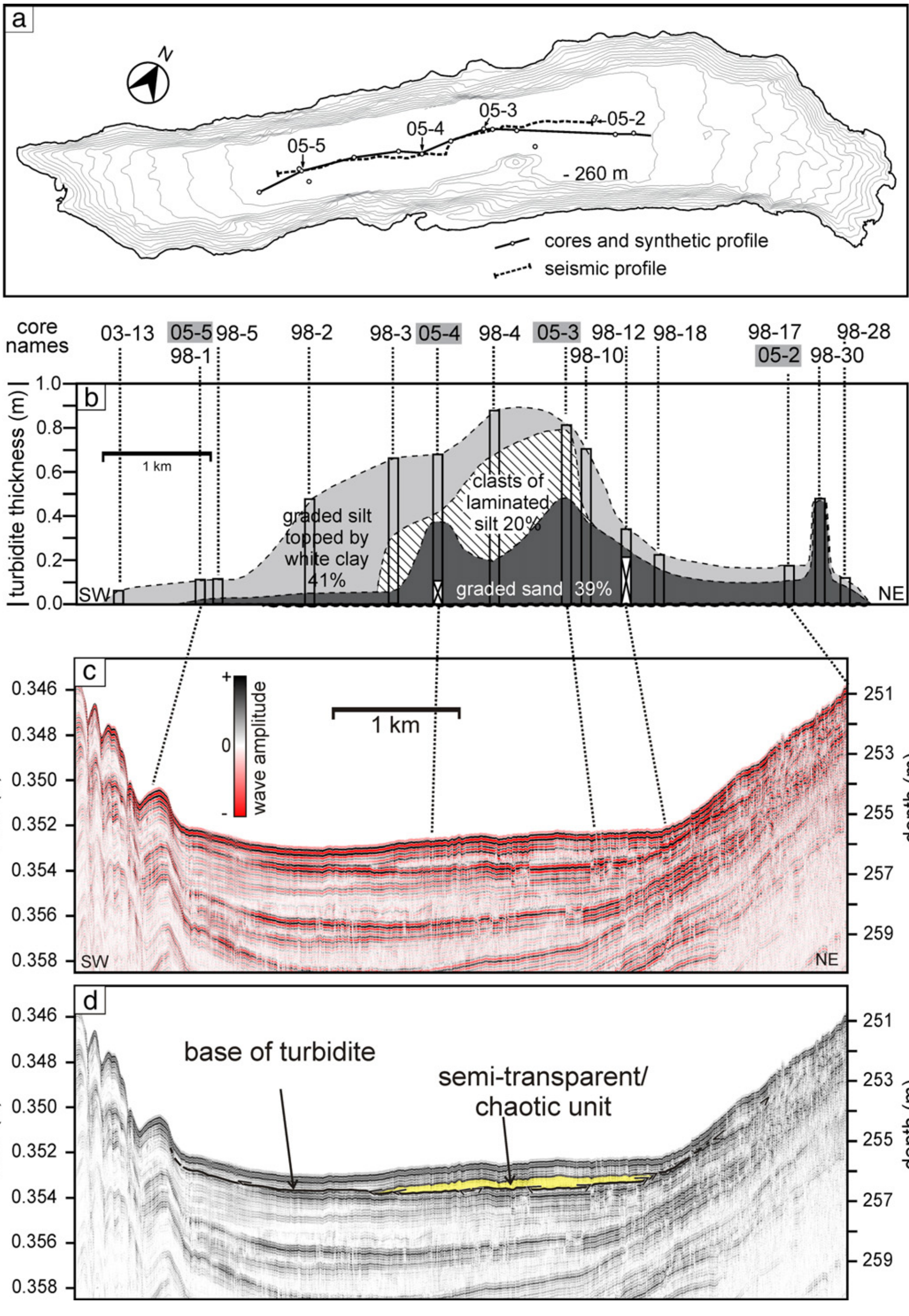

Fig. 5. Longitudinal turbidite profiles from core and seismic data. (a) Location map of longitudinal profiles (b) Synthetic sedimentary profile drawn from core data with turbidite thickness and proportional sub-units (lithology). Vertical exaggeration is 2100x. (c) Raw 3.5 kHz seismic profile (d) Interpreted seismic profile with onlapping reflections and semi-transparent/chaotic facies at the base of the turbidite. Vertical exaggeration is 240x.

deposit throughout the lake basin. It averages 70 to 90 cm thick in the central and deepest parts of the lake, whilst thinning out toward the lake basin delta slopes in both directions (NE and SW). The turbidite is also longitudinally graded as the silt content increases towards the SW, where sand percentages are low. A sediment hiatus below the turbidite deposit shows that erosion happened during the sedimentological event. The identified missing sediment intervals decrease in thickness from NE toward SW, indicating weakening erosion toward that direction. Basal sediment hiatuses disappear beyond the core 98-2 location, which points to the absence of basal erosion in the SW part of the deep lake basin (Fig. 5b). Sediment clasts of thinly laminated, silty sediment occur within the turbidite and have the same lithology and mean granulometry as the hemipelagic deposits. As seen in core BR05-4 (Fig. 4), these clasts can be as large as 50 cm and occur mostly at the transition between the graded sand below and the silty units above (Fig. 5b).

Based on the reconstructed lithology transect (Fig. 5b), the turbidite deposit can be proportionally subdivided into 41% of graded silt, 39% graded sand and 20% of incorporated sediment clasts.

Detailed lithology comparison of the sediment clast (from core BR05-4, Fig. 4) and sampled hemipelagic layers (core BR03-10; Anselmetti et al., in press), reveal the good correlation between a 10-cm-thick sediment interval and the 165° rotated clast (Fig. 6A). In a previous study by Anselmetti et al. (in press), this hemipelagic interval was dated by the 1963 AD atmospheric fallout time marker. The screening of all sampled cores indicates that the possible original clast location is situated in the central deep basin toward the NE (light blue area, Fig. 6B). These evidences indicate that i) sediment erosion certainly occurred at the base of the moving flow, at least in the deep basin NE part, and that ii) sediment clasts were possibly transported over a distance up to 4 km before they settled down into the large turbidite deposit.

4.3. Seismic profiles

The 3.5 kHz seismic profiles across Lake Brienz image the lake floor at high vertical resolution and with a penetration of maximum 35 m sediment thickness. A ~6 km long longitudinal profile (Fig. 5a, c and d) shows a thick, prominent and extensive onlapping seismic unit near the sediment surface (Fig. 5d), which correlates to the turbidite sedimentary deposit observed in the cores. This turbidite seismic unit has an acoustically transparent/chaotic lower unit (in yellow), which coincides with

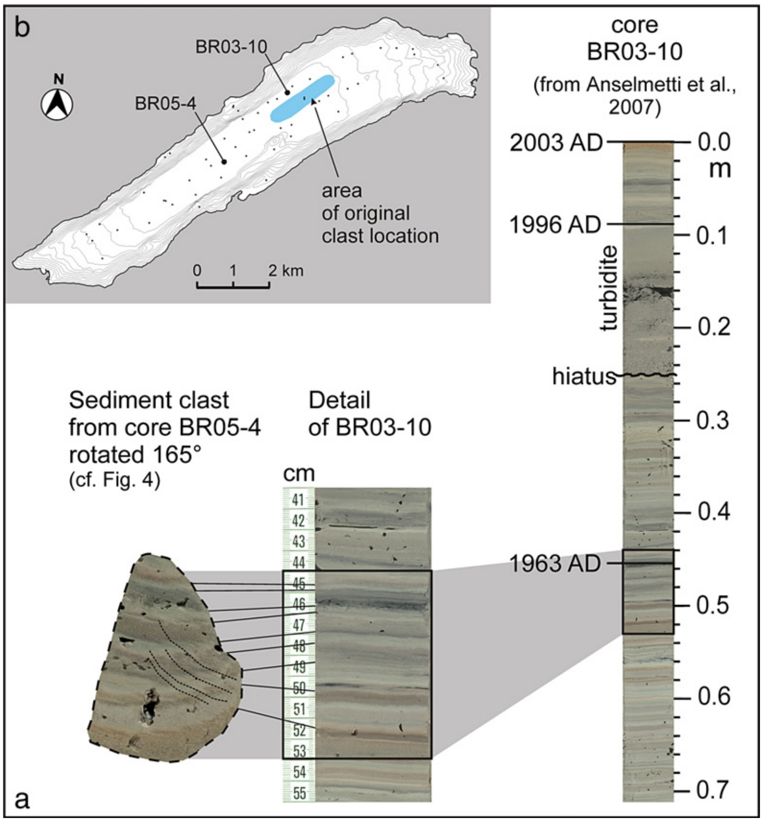

Fig. 6. (A) Lithology correlation between the sediment clast embedded in 1996 AD turbidite (detail of core BR05-4, cf. Fig. 4) and hemi-pelagic sediments (core BR03-10; Anselmetti et al., in press). The clast comes from sediment layers situated stratigraphically below the 1996 AD turbidite. (B) The possible original clast location is situated in the central deep basin (light blue surface). Sediment clasts were possibly transported over a distance up to 4 km before they settled down into the large turbidite deposit.

locations where sediment cores contain at least 10–15 cm of graded sand at the base (Fig. 5b).

In contrast to other large turbidite deposits imaged by seismic reflection data (Schnellmann et al., 2005), the 1996 AD turbidite seismic unit has a continuous and high-amplitude seismic facies at its top displaying a lower transparent/chaotic facies restricted to its thickest portions. This can be explained by the particular stratigraphic position of the turbidite bed, which is situated only 10–20 cm below the water–sediment interface. Due to the strong water–sediment density contrast of the lake floor, strong reverberating surface reflections are produced that mask the normally transparent facies of graded silt which comprises the uppermost lithology of the turbidite (Fig. 4). The strong seismic reflection corresponding to the base of the turbidite bed is caused by the density change from turbidite basal sand above to the underlying hemipelagites (Fig. 5c). Because this change results in a prominent downcore decrease in impedance, the high-amplitude basal reflection of the turbidite has inverted polarity compared to the lake floor reflection (Fig. 5).

4.4. Distribution

As previously mentioned (Sections 4.2 and 4.3), the geographical distribution and sediment thickness of the 1996 AD large turbidite can be traced on both sediment cores and seismic lines. The map inferred from the core data (Fig. 7) shows that the turbidite deposit extends over a surface of ~8.5 km^2 covering also areas outside the flat part of the lake bottom. Turbidite thickness values vary between 0 and 0.9 m. Smooth isopach lines are a result of relatively sparse core locations. The main sediment depocenter is situated near the midpoint of the lake, and thickness values decrease toward the SW and NE. A second depocenter, with maximum values of 0.45 m, is situated 260 m toward the NE from the main one, i.e., closer to the Aare river mouth (Fig. 7). The longitudinal core profile (Fig. 5b) indicates that this smaller depocenter consists mostly of sand.

The resulting interpolated vertical profile (Fig. 8a), calculated from the turbidite thickness map, is reported on the bathymetric profile (Fig. 8b). On the Lütschine side of the lake (toward SW) the turbidite deposit disappears above 254 m water depth, whereas on the Aare side (toward NE) the turbidite deposit disappears above 246 m water depth. This implies that the turbidite traveled through the lake from NE to SW.

4.5. Volume and mass

The total wet volume of the turbidite deposit, calculated from interpolated core data, is $2.72*10^6$ m^3. According to the respective lithology proportions in the sedimentary cores (Fig. 5b), this volume is composed of $1.12*10^6$ m^3 graded silt, $0.54*10^6$ m^3 sediment clasts and $1.06*10^6$ m^3 graded sand (Table 2). The turbidite

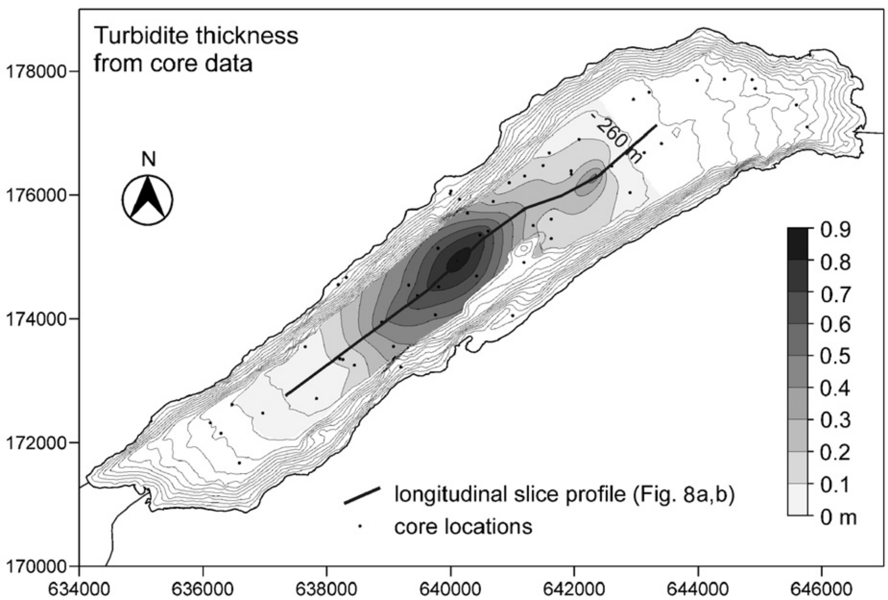

Fig. 7. Turbidite thickness map (with Swiss grid coordinates) inferred from core data. Location of sediment cores and interpolated longitudinal profile are indicated as black dots and plain line, respectively.

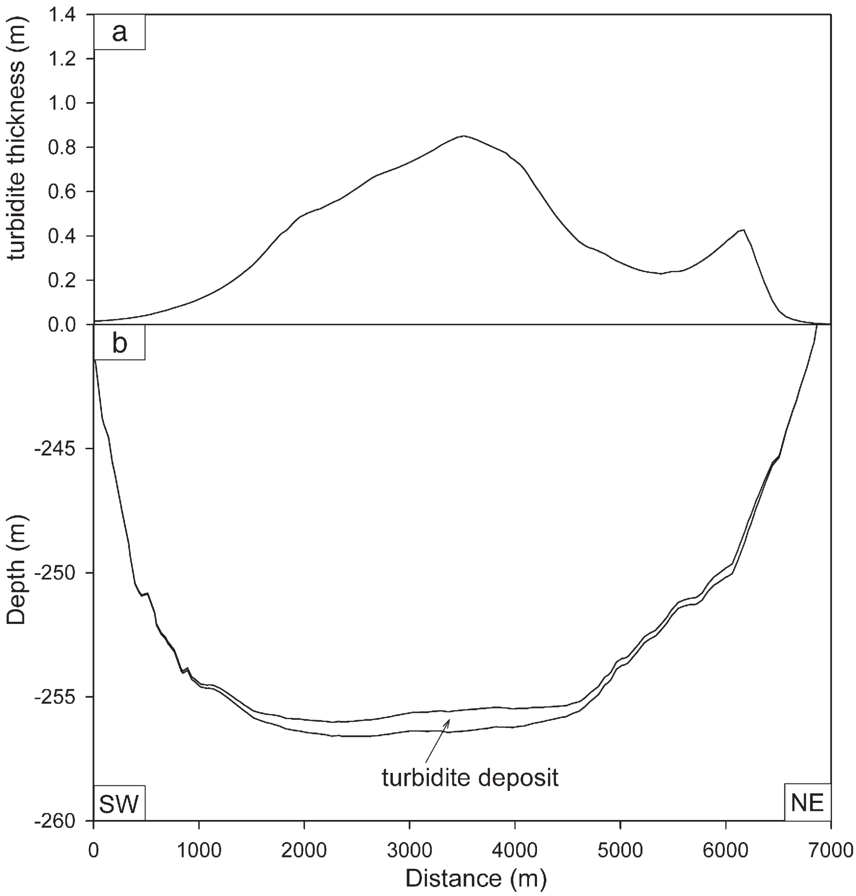

Fig. 8. (a) Interpolated thickness profile of the large 1996 AD turbidite calculated from core data. Vertical exaggeration is ~2100x. (b) Bathymetric longitudinal profile of the lake floor and turbidite deposit. At equivalent water depth, the turbidite deposit is thicker toward the NE side of the lake. Vertical exaggeration is ~230x. For profile location refer to Fig. 7.

porosity varies between 66–73% for the graded silt and sediment clasts decreasing to 52% for the graded sand (Table 2). Hence, corrected dry volumes are $0.30*10^6$ m^3 for graded silt, $0.18*10^6$ m^3 for sediment clasts and $0.51*10^6$ m^3 for graded sand. The total turbidite dry volume is $0.99*10^6$ m^3 and its equivalent dry sediment mass is $2.62*10^6$ t (Table 2).

Table 2
Mean bulk density, mean porosity and volumes (wet and dry) for the three 1996 AD turbidite lithological classes

	Graded silt	Clasts	Graded sand	Total
Mean bulk density (g/cm^3)	1.41	1.55	1.78	–
Volume wet ($*10^6$ m^3)	1.12	0.54	1.06	2.72
Mean porosity (%)	73	66	52	–
Volume dry ($*10^6$ m^3)	0.30	0.18	0.51	0.99
Dry sediment mass ($*10^6$ t)	–	–	–	2.62

Dry sediment mass is calculated with a given density of 2.65 g/cm^3.

5. Discussion

The 1996 AD turbidite sediment layer represents an exceptionally large deposit at the scale of the Lake Brienz basin. Its in-situ volume ($2.72*10^6$ m^3) and its sediment dry mass ($2.62*10^6$ t) amounts to ~8.7 yr of the lake average total annual input ($3.02*10^5$ t/yr for 1997–2004) and 20-times the Aare river input ($1.28*10^5$ t/yr for 1997–2004; Finger et al., 2006).

5.1. Source area

The thickness distribution of the large turbidite deposit clearly points to the Aare delta region (NE) as the source area (Fig. 8). The mineralogical assemblage of sediment grains found on the 'Brienzi' dead body (Thali et al., 1998) also points unequivocally toward the Aare delta as original storage area. Furthermore, if the human corpse was released in the Aare Delta, the counterclockwise lake circulation (Nydegger, 1967, 1976; Sturm, 1976) would indeed carry the floating body to the north shore, where it was found. Additionally, the presence of sand grains (300 μm grain size) at the base of the turbidite deposit is very likely indicating that the sediment transport started somewhere in the proximal part of the Aare delta where such sands can be found.

5.2. Timing of the turbidite and associated events

CTD measurements (Zeh, 1997) show that the sedimentological event happened between March 26th and April 30th 1996 (Fig. 3). But the 'Brienzi' corpse occurrence helps to further refine the dating, because it was found on May 1st 1996 in Oberried (Ammann, 1997), about 7 km away from the Aare river mouth. Lake Brienz surface currents flow from the Aare river mouth to Oberried, along the north coast of the shore, with speeds of 74–160 m/h (Nydegger, 1967, 1976). This indicates that at least 2 days were required to transport the 'Brienzi' corpse from its source area (Aare delta) to the place where it was found. Accordingly, the original mass movement/flow probably started, as the dead body was released into the water before April 29th 1996. This incident combined with the small tsunami wave observed by Aarekies AG workers can be related to the starting of an underwater mass movement/flow, allowing to further refine the dating of the event starting time to April 24th 1996 around 8:00 GMT.

5.3. Trigger

The major factors responsible for initial subaqueous slope instabilities in continental margins and active delta areas are: earthquakes, sediment loading, rapid water-level changes, cyclic loading by waves and biochemical processes (e.g., generation of pore gasses). These factors may combine with complex interactions to increase stresses or lower sediment strength and lead to sediment instability (Coleman and Prior, 1988; Hampton et al., 1996; amongst others). Applied to the context of Lake Brienz, the factors likely to trigger a slope failure are, in decreasing order of likely impact: earthquake, explosion, river flood, wind waves, lake-level fluctuation, internal seiche, sediment dredging, in-situ biochemical processes, and normal delta accumulation.

1) Earthquake: none of the intensities of local or regional earthquakes occurring in Switzerland in 1996 (Baer et al., 1997; Fäh et al., 2003) could have induced any type of mass movement in Lake Brienz.
2) Explosion: a rockslide hit the main road near Iseltwald on February 21st 1996 and 297 kg of Telsit explosive were used at 13:30 GMT on April 24th 1996 to clear the road from blocks. This explosion cannot be responsible for the turbidite triggering as it happened after the initial sedimentological event (April 24th 1996, 8:00 GMT). In addition, the 6 km distance to the Aare delta is too large for this explosion to be able to trigger any subaquatic mass movement in that area. Furthermore, such explosions are usually not detonated at once, so that this type of artificial seismic shaking becomes even weaker (Donat Faeh, pers. comm.).
3) River flood: the Aare river flow record in Brienzwiler for 1993–1996 AD (Fig. 9) shows that the large turbidite deposit was initiated before the summer flood season, and during a period of quite stable low river flow conditions. During beginning of April 1996, i.e., in the period preceding the initiation of the turbidite, maximum daily Aare river flow values where mostly restricted to 20–40 m^3/s and reached once a small peak of 52 m^3/s (April 23rd). This river regime is very weak in comparison to normal summer river flows (80–100 m^3/s), and even weaker in comparison to the large summer flood events, which are characterized, between 1993 to 1996 AD, by flow rates of 100–330 m^3/s. Thus the 1996 AD turbidite event is not likely to have been mainly triggered by a large river flood.
4) Wind waves: MeteoSwiss wind data measured at the Brienz–Kienholz station (1 km away from the Aare river mouth) show that only light breezes blew from 1993-1996 AD in that area (Fig. 10a). Mean daily values ranged from 0 to 11 km/h and maximum wind speed only reached 38 km/h. Proportionally, the April 1st–April 24th 1996 time interval was not particularly windy either: breeze events in 1993 AD (April 24–28th), in 1994 AD (January 26–29th) and in 1995 AD (January 24–26th) display larger values for both mean and maximum wind speed values (Fig. 10a, black arrows). The strongest April 1996 winds blew from April 21st to April 23rd from the East (grey arrow, Fig. 10b and c) but they only reached a maximum speed of 23.5 km/h (April 22nd at 16:50 GMT). Considering the Easterly direction of these wind events (Fig. 10b), the fetch in the Aare delta area was low (less than 2 km). Speed intensity, fetch and duration are key parameters controlling wind-wave formation. The low local fetch, added to weak winds, prevented any high wind-waves formation during the period preceding the turbidite triggering as well as on the day of the event itself (April 24th 1996). This

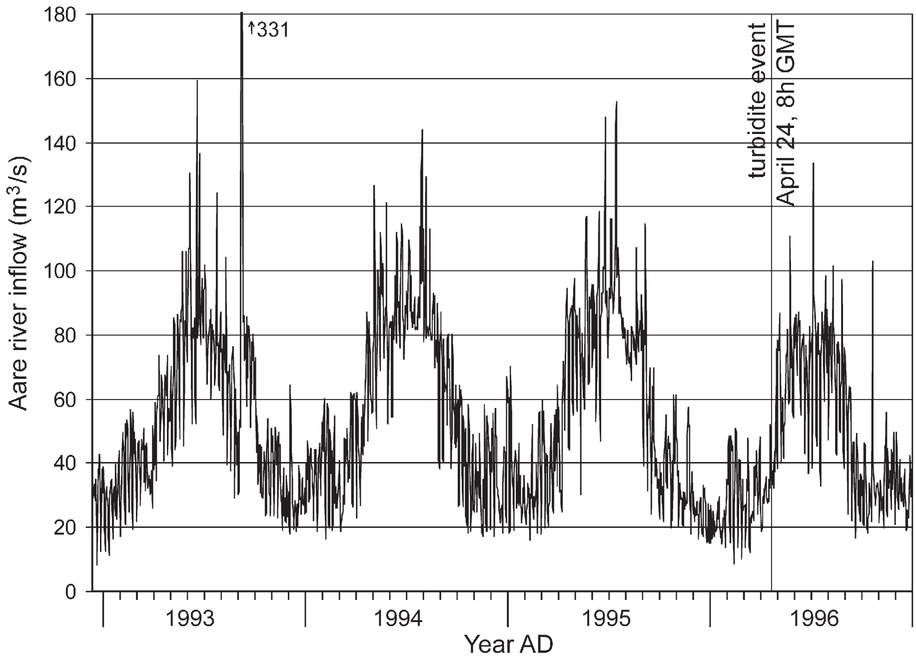

Fig. 9. Maximum daily flow of Aare river (m^3/s) measured in Brienzwiler from 1993–1996 AD (Bundesamt für Umwelt BAFU - Abteilung Landeshydrologie und-geologie BWG, 1993–1996a). The turbidite triggering date is indicated by a vertical line (April 24th 1996).

interpretation is also confirmed by the local observations which attest that the lake surface was very calm on April 24th 1996. Therefore, a significant lowering of the lake's wave-base and enhanced wave action due to wind-waves can probably be excluded as the turbidite trigger.

5) Lake-level fluctuation: the Lake Brienz fluctuations recorded during the period 1993-1996 AD (Fig. 11) show that no low- or year-frequency lake lowering occurred before the turbidite deposit was triggered. To the contrary, Lake Brienz level continually rose from 563.0 to 563.8 m until June 1996. Moreover, this scheme of low lake-level in March, followed by rapid lake-level rise in April, is a replica of the 1995 AD lake-level scenario. Thus, a primary influence of lake-level changes on the turbidite triggering can be excluded.
6) Internal seiche: the lacustrine seiches can create important waves at thermocline level during lake water stratification (Bohle-Carbonell, 1986). They have up to 5 m amplitude near the coast and can induce water speed of 45 cm/s (Lemmin, 1998; Lemmin et al., 2005). Near the lake shore, seiches have the potential to put sediment in suspension contributing, therefore, to sediment redistribution. But water temperature data shows that the Lake Brienz thermocline was not fully formed until mid-May 1996 (David Finger, pers. comm.), which means internal seiche is probably not the original turbidite trigger.
7) Sediment dredging: at the time the 1996 AD turbidite deposit was initiated, sediment-mostly gravel and coarse sand-was being dredged offshore from the old Aare delta at water depths between 8 and 10 m, i.e. from the old upper delta planar slope. Considering that sediment dredging is 'unloading' the former upper delta and that gravel and coarse sand are absent in the turbidite deposit, it is very unlikely that sediment dredging was the triggering of the turbidite event.
8) Biochemical processes: biological activity is present in lacustrine sediment with high organic content, so that pore gasses (e.g. methane) can be generated. The biogenic gas production can potentially change the inter-particle cohesion and friction and reduce sediment strength (Coleman and Prior, 1988). These processes are not well-known in ultra-oligotrophic Lake Brienz, but recent sediment of small eutrophic lakes shows that increase in temperature and/or in organic matter supply lead to higher methane production rates (Kelly and Chynoweth, 1981). More recently, it has been shown that methane production in littoral sediments of Lake Constance follows the same seasonal trend as sediment temperature, with a peak of methane production rate in late summer and

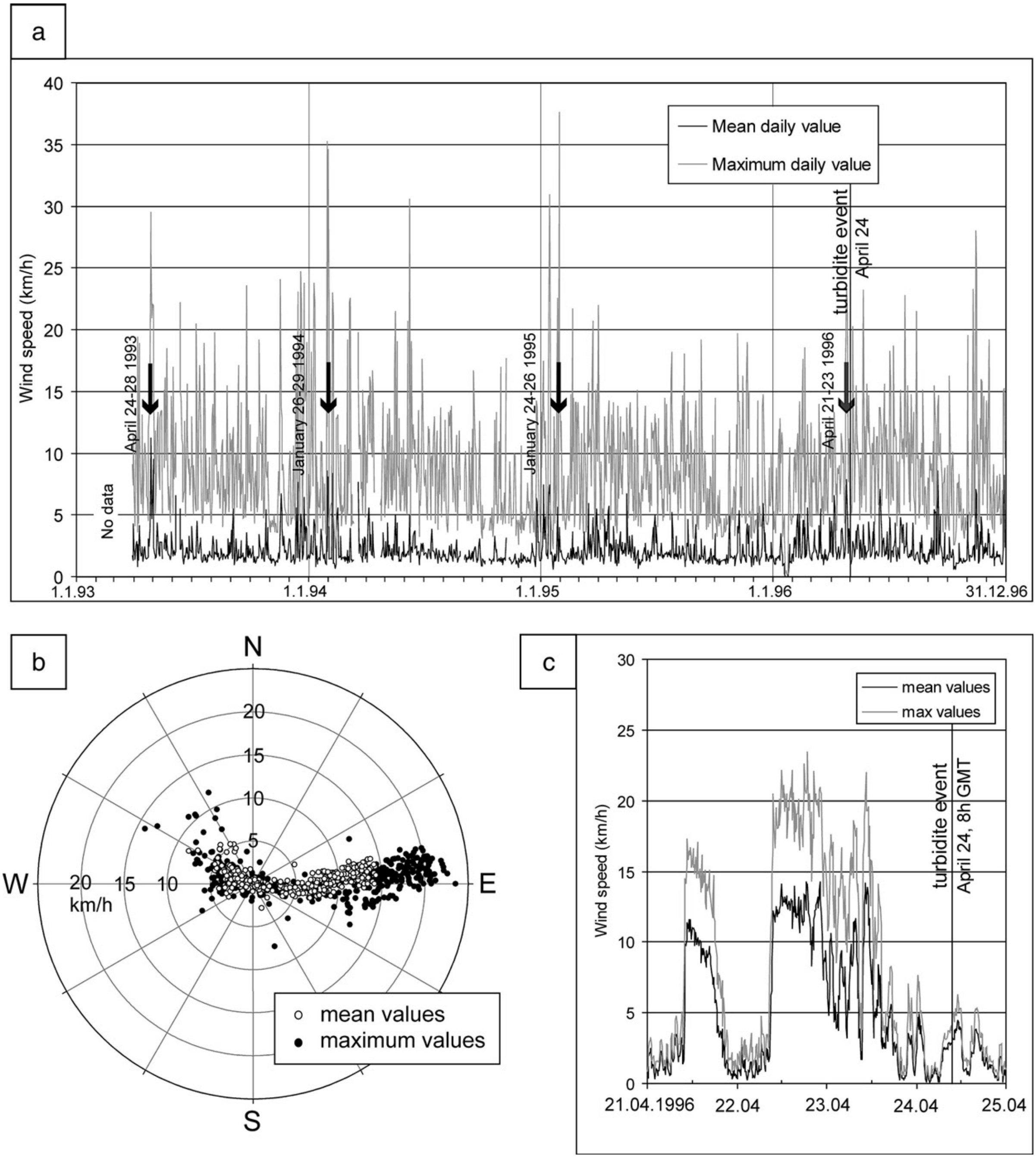

Fig. 10. Wind data from Brienz–Kienholz (MeteoSwiss, 1993–1996). (a) Mean and maximum daily wind speed (km/h) from 1993 to 1996 AD. Black arrows indicate strongest 1993–1996 wind events. The turbidite triggering date is indicated by a vertical line (April 24th 1996). (b) Polar plot of wind direction and wind speed (km/h) measured over 10 min period (April 21st–24th 1996). (c) Mean and maximum wind speed (km/h) measured over 10 min period (April 21st–24th 1996).

low values in winter (Thebrath et al., 1993). As Lake Brienz and Lake Constance have the same seasonality pattern, Lake Brienz production of biogenic gasses is then most probably low in April. In addition, the continuously decreasing nutrient supply to Lake Brienz since the early 1980’s (Müller et al., in press) favours a mean decrease in biogenic gas production for the past decades. Thus, biochemical processes most probably did not play the main role in triggering the April 24th 1996 turbidite event.

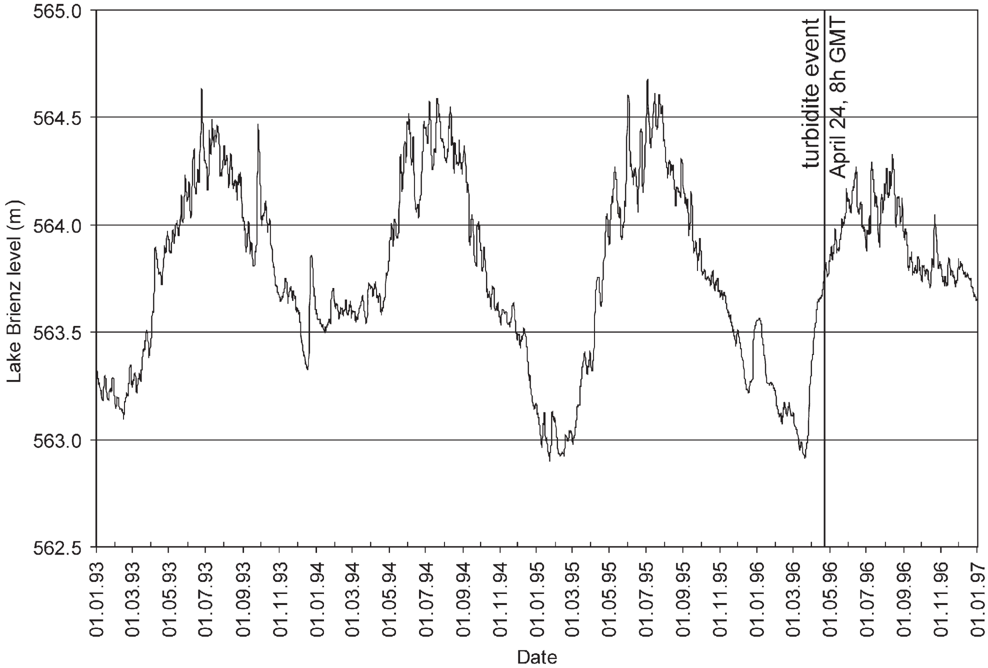

Fig. 11. Lake Brienz level change (alt. m) from 1993–1996 AD (Bundesamt für Umwelt BAFU - Abteilung Landeshydrologie und-geologie BWG, 1993–1996b). The turbidite triggering date is indicated by a vertical line (April 24th 1996).

9) Normal delta accumulation: the high sedimentation rates of the Aare delta (0.7–1 cm/yr on levees; Anselmetti et al., in press) can result in increasing the sediment loading and may also lead to the formation of excess pore pressure (Sultan et al., 2004). Both factors reduce slope stability to a critical state where sediment failure may occur, especially in the proximal delta area, where the slope is steep (maximum slope angle of 17°, Adams et al., 2001). So, normal delta accumulation is possibly the trigger of the 1996 AD turbidite event.

The evidences described above indicate that the triggering of the 1996 AD large turbidite deposit is likely to have been caused by normal sediment accumulation in the Aare proximal delta area and probably due to reaching the slope stability threshold. However, we cannot rule out, that a minor shaking of a weak earthquake, a small increase in Aare river inflow, or any type of subtle interaction between the possible triggering factors, may have been the final initialization of this overdue event.

5.4. Flow mechanism

The stratigraphic position of sediment clasts in the 1996 AD turbidite deposit (Fig. 5b) indicates that sequences of hemipelagic lacustrine sediment were incorporated into the moving flow during the sedimentological event. In addition, the original clast location (Fig. 6B) evidences that sediment erosion was certainly occurring at the base of the moving flow when it reached this area in the deep lake basin. The gradient of decreasing basal erosion toward SW also documents that erosion weakened as the flow crossed the deep flat basin, and that erosion ended before the flow reached the location of core 98-5 (Fig. 5b).

The longitudinally and vertically grading of the turbidite deposit (Fig. 5b), added to the evidence of basal erosion, can only be explained with a mixed flow rheology of turbidity current and dense flow. Sedimentological models for the generation of debrite–turbidite beds during the same flow event were synthesized by Talling et al. (2004). They consist of five variants: a) turbidity current is formed by mixing and dilution of an initial debris flow; b) debris flow forms by erosion of muddy sea-floor by initial turbidity current; c) loading of basin margin by initial turbidity current triggers secondary debris flow; d) deceleration of initial turbidity current; e) deceleration of initial low-coherency debris flow. In our case study, the sedimentological evidence excludes model d), as the deceleration of an initially true turbidity current cannot explain the presence of sediment clasts in the deposit. But all other models (a–c and e) are suitable options to explain the generation of the 1996 AD turbidite deposit. Mohrig and Marr (2003) and Illstad et al. (2004) also pointed out that sandy debris flows tend to take on ambient water, expand and become turbulent when they accelerate. This leads to a direct transition from debris flows to turbidity current, which–in the case of an original debris flow–applies well to our case.

The observed small tsunami wave on April 24th 1996 also contributes to constraining the possible mass-transport mechanism. Tsunami waves, when not triggered by earthquakes, can be generated by underwater slides through two different mechanisms: i) a piston-like effect, where the moving underwater slide pushes water upward and laterally above its frontal part and downward at the rear of the failure; ii) and a nonpiston-like interaction between the water and the slide, where the slide, transformed into a turbidity current (or debris flow?), transfers a significant amount of energy to the water (Fine et al., 2005). At present, it is not possible to define, which mechanism, the piston-like or the nonpiston-like, could have caused the Lake Brienz tsunami wave, but both processes presuppose an original underwater slide. The occurrence of the tsunami wave, together with the release of the ‘Brienzi’ corpse into the lake waters, point to a slope failure in the proximal Aare delta area, which induced the tsunami wave, and ultimately developed into the final turbidite deposit. Under these conditions, the steep upper Aare delta slope angle (maximum 17°; Adams et al., 2001) could easily provide the necessary acceleration to transform the slide into a turbidity current or debris flow, and to travel across the low gradient Lake Brienz deep basin.

5.5. Ecological significance of the event

The gravity flow, which deposited in 1996 AD the large sediment bed in deep Lake Brienz, made its way through the basin almost undetected at the exact time it happened. It caused, however, a great sedimentological impact on the lake floor due to the very large volume of sediment that was eroded and redistributed inside the lake basin. This impact was particularly strong in the lake deep waters because the transparency was greatly reduced in the lowermost 50 m, taking 6 mo to return to pre-event values (Fig. 2a). Moreover, oxygen concentrations in lake deep waters decreased significantly. This was probably due to the large volume of anoxic pore water released by the slope instability and incorporated into the flow, thus becoming redistributed throughout the lake basin. It took a year and a half for the lake waters to recover from the turbidite event and to reach normal oxygen contents in the deepest areas. As Lake Brienz is very deep and ultra-oligotrophic, the low oxygen concentration apparently did not cause any important ecological impact on the lake ecosystem. But in sensitive lake environments, e.g., where a lowering of oxygen concentration could threaten deep water biologic communities, the impact would be much larger. Furthermore, such an event could change redox conditions at the sediment–water interface inducing remobilization and possible release of redox sensitive elements (e.g., Fe, Mn) and their associated components (e.g., phosphate). For example, in September 1994, strong flood-induced turbidity currents reached Lake Lugano’s deep basin and produced a deterioration of the surface water quality by inducing a vertical water flux, which raised phosphorus-rich and oxygen-poor deep waters from the deep hypolimnion to higher parts of the lake (De Cesare et al., 2006). In lakes with highly polluted sediments, this process could even have a much larger ecological impact with catastrophic consequences.

5.6. Comparison with related turbidite deposits

The Lake Brienz large turbidite shows the same transparent/chaotic internal seismic facies and strong basal seismic reflection than their lacustrine and large marine counterparts (Cita and Aloisi, 2000; Hieke, 2000; Rebesco et al., 2000; Schnellmann et al., 2005, amongst others) but due to the proximity of the deposit with the lake water–sediment interface, reflection artifacts partially hide the otherwise transparent facies. The 1996 AD turbidite can nevertheless be compared to these similar deposits, and like large turbidites from other lakes or much larger basins, it forms a very good and extensive seismic and stratigraphic marker.

The Lake Brienz large turbidite includes sediment clasts that were most certainly eroded at the base of the moving flow. In Lake Lucerne, where large turbidite deposits are also the secondary distal by-products of original mass flows combined with tsunami and seiches action, embedded clasts are absent (Schnellmann et al., 2005). This contrast can be explained by the depositional flow mechanism: in Lake Lucerne, turbidite deposits where certainly formed from suspension clouds, i.e. with a pure turbulent rheology; whereas Lake Brienz deposit points to a mixed flow turbidity current/dense flow rheology. In the marine turbidite deposits that evolved distally from mass movements or mass flows, embedded sediment clasts seem to be rare, but it is speculative to attribute this difference to a particular sedimentological process rather than to a sparse core sampling. Indeed, sedimentary model for the downslope evolution of a turbidity current, inferred from the rock record (Mutti et al., 2003), signals the presence of 'rip-up mudstone clasts' in the proximal stage of bipartite turbidity currents. Sediment clast presence is also attested in the Herodotus basin turbidite (Reeder et al., 2000), which shows similar granulometry and texture distribution to the 1996 AD Lake Brienz turbidite.

Large graded sediment deposits that evolved distally from an original slope failure, are also named 'homogenite', 'megaturbidite' or 'megabeds' (Cita and Aloisi, 2000; Reeder et al., 2000; Zuffa et al., 2000, amongst others). The 'type B homogenite' in the eastern Mediterranean (Cita and Aloisi, 2000) displays a grain size distribution, thickness gradient and partly erosive base very similar to the turbidite deposit of Lake Brienz but on a much smaller scale. The homogenite in Lake Le Bourget, a sediment layer with a thin graded base and homogenous upper part (volume $\sim 2*10^5$ m^3) was deposited after a violent earthquake in 1822 AD (Chapron et al., 1999). Like in Lake Brienz, the Lake Le Bourget sediment deposit also evolved distally from an original slope failure into a prominent partly graded layer, but due to the distal position of the slide scar, its grain-size is dominated by clays and fine silts, instead of the silts and sands in Lake Brienz. Similarly to the Lake Brienz large turbidite, megaturbidites in Lake Lucerne are normally graded with a sandy base and a distinct white clay top (Schnellmann et al., 2005). This top clay layer might be specific to the sediment input of those lakes (i.e. glacier influenced catchment) or more generally, to lacustrine decantation processes.

In the Ionian basin, the Augias megaturbidite is presumably triggered by a tsunami wave hitting the Sirte Gulf shoreline, following the catastrophic eruption of the Santorini caldera at 3500 y BP (Cita and Aloisi, 2000) or by an earthquake due to the volcanic activity itself (Hieke and Werner, 2000). Older megaturbidites from the Ionian and Sirte abyssal plains might have been also triggered by earthquakes and/or tsunamis (Hieke, 2000). The Pleistocene Herodotus Basin megaturbidite deposit (Reeder et al., 2000) is interpreted to be the result of an initial slide-debris flow event that evolved downslope into a megaturbiditic current with the possible triggering factors including low sea-level, seismic activity, sediment oversupply, degassing of gas hydrates or clathrates and impact by tsunami wave. The Late Pleistocene megabeds from Escanaba Trough are interpreted as outburst (or 'jökulhlaups') of glacial Lake Missoula (Zuffa et al., 2000). In Lake Constance, two graded clastic layers are interpreted as hyperpycnite deposits related to catastrophic floods induced by the failure of two large landslide dams in the Rhine river catchment (Schneider et al., 2004). In Lake Lucerne, megaturbidites are interpreted as combined products of sediment put into suspension by multiple sliding, tsunami and seiches action following large earthquake events (Schnellmann et al., 2005). The 'Grand Banks' earthquake of 1929 AD initiated multiple slumping and a subsequent large turbidity current, which resulted in a large turbidite deposit (185 km^3) consisting mostly of sand (Piper and Aksu, 1987; Piper et al., 1999). In the Var river canyon cored sediment indicate that over the past 100 yr, 2–3 slide-induced turbidites have been recorded (Mulder et al., 2001) including the 1979 AD human-induced slide event off Nice (Piper and Savoye, 1993) which lead to a tsunami (Assier-Rzadkiewicz et al., 2000). These examples indicate that the triggering of many large turbidites are often related to catastrophic or exceptional events.

To the contrary, the Mississippi delta study has shown that bar failures occurred repeatedly 1 to 4 yr after major floods in response to a variety of triggering mechanisms with complex feedback mechanism, and more generally, that a small change in prevailing conditions can trigger a submarine landslide in a context of rapid sedimentation (Lindsay et al., 1984). The Lake Brienz case study demonstrates likewise in the lacustrine realm, that a slope failure due to normal delta accumulation can lead to an exceptionally large deep-basinal turbidite deposit and even induce a small tsunami wave.

6. Conclusion

Sediment core and high-resolution seismic data reveal that the 1996 AD large turbidite deposit in Lake Brienz (Switzerland) consists of normally graded sand to silt grain-sized sediment topped by a thin white clay-sized layer, and contains sediment clasts of hemipelagic sediments. It is a maximum of 90 cm thick and thins out toward the lake basin ends. It correlates to prominent onlapping unit on seismic record. Thickness distribution maps show that turbidite deposit extends over ~ 8.5 km^2 and has a total volume of $2.72*10^6$ m^3, which amounts ~ 8.7 yr of the lake's total sediment input.

A series of observations from the water column (increase in turbidity and lowering of oxygen content, release of an old human corpse, small tsunami wave) can all be linked to the onset of the turbidite and date the event to April 24th 1996 at about 8:00 GMT. This sedimentological event began in the Aare delta area, certainly as a small slope failure, transforming into a large mass movement/grain flow, which traveled down the delta slope to reach the flat 260 m deep lake basin.

Along the way, it eroded sediments and incorporated clasts of hemipelagic sediments, to finally deposit as a longitudinally and vertically graded sediment layer. In-situ CTD measurements show that transparency and oxygen concentrations of the lake deep waters were greatly impacted by this sedimentological event: it took 6 mo for transparency to return to normal values and a year and a half to reach normal oxygen contents.

At the scale of the Lake Brienz basin, the 1996 AD turbidite deposit is an exceptionally prominent and large sediment layer similar to large turbidites described in the marine record. However, in contrast to many known large turbidite events, no obvious triggering (earthquake, explosion, flood, wind storm, lake-level change, seiche or sediment dredging) was needed to initiate the process. It was most likely initiated by a delta slope failure due to normal sediment accumulation. But the induced mass movement/grain flow, which led to the large turbidite deposit, induced a small 'tsunami-like' wave of at least half metre wave height and maximum of 30–40 min wave period on the lake surface. These results open new perspectives for the interpretation of large turbidite deposits in the sedimentary and rock record and as well as for their evaluation as natural hazards.

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